

Retrieval of Cloud Microphysical Properties from MODIS and AIRS

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ABSTRACT

The Moderate Resolution Imaging Spectroradiometer (MODIS) and the Atmospheric Infrared Sounder (AIRS) measurements from the NASA Earth Observing System *Aqua* satellite enable global monitoring of the distribution of clouds during day and night. The MODIS is able to provide a high-spatial-resolution (1–5 km) cloud mask, cloud classification mask, cloud-phase mask, cloud-top pressure (CTP), and effective cloud amount during both the daytime and the nighttime, as well as cloud particle size (CPS) and cloud optical thickness (COT) at 0.55 μm during the daytime. The AIRS high-spectral-resolution measurements reveal cloud properties with coarser spatial resolution (13.5 km at nadir). Combined, MODIS and AIRS provide cloud microphysical properties during both the daytime and nighttime. A fast cloudy radiative transfer model for AIRS that accounts for cloud scattering and absorption is described in this paper. One-dimensional variational (1DVAR) and minimum-residual (MR) methods are used to retrieve the CPS and COT from AIRS longwave window region (790–970 cm^{-1} or 10.31–12.66 μm , and 1050–1130 cm^{-1} or 8.85–9.52 μm) cloudy radiance measurements. In both 1DVAR and MR procedures, the CTP is derived from the AIRS radiances of carbon dioxide channels while the cloud-phase information is derived from the collocated MODIS 1-km phase mask for AIRS CPS and COT retrievals. In addition, the collocated 1-km MODIS cloud mask refines the AIRS cloud detection in both 1DVAR and MR procedures. The atmospheric temperature profile, moisture profile, and surface skin temperature used in the AIRS cloud retrieval processing are from the European Centre for Medium-Range Weather Forecasts forecast analysis. The results from 1DVAR are compared with the operational MODIS products and MR cloud microphysical property retrieval. A Hurricane Isabel case study shows that 1DVAR retrievals have a high correlation with either the operational MODIS cloud products or MR cloud property retrievals. 1DVAR provides an efficient way for cloud microphysical property retrieval during the daytime, and MR provides the cloud microphysical property retrievals during both the daytime and nighttime.

1. Introduction

Clouds play an important role in the earth's water and energy budgets. Their impact on the radiation budget can result in a heating or a cooling of the planet, depending on the radiative properties of the cloud and its altitude (Stephens and Webster 1981; Stephens et al. 1990). Because clouds have such a large effect on the earth's radiation budget, even small changes in their abundance or distribution could alter the climate more

than the anticipated changes from trace gases, aerosols, or other factors associated with global change.

Cloud parameters, such as cloud-top pressure (CTP), effective cloud emissivity or effective cloud amount (ECA), cloud particle size (CPS) in diameter, cloud optical thickness (COT) at 0.55- μm wavelength, ice water path (IWP), and liquid water path (LWP), are important to weather and climate prediction (Diak et al. 1998; Bayler et al. 2000; Kim and Benjamin 2000; Stephens et al. 1990).

The capability to make cloud microphysical property measurements from instruments on the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) *Terra* and *Aqua* satellites is unprecedented. These unique global measurements include radiances from the visible (VIS), near-infrared

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(NIR), infrared (IR), and microwave spectral regions and are available at spatial scales from a few hundred meters to a few tens of kilometers. The twice-daily temporal resolution makes these instruments well suited for the comprehensive study of some significant weather events such as tropical cloud systems and processes (TCSP). The EOS instruments that will be utilized in this study include the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Atmospheric Infrared Sounder (AIRS).

MODIS on the EOS *Terra* and *Aqua* satellites provides multispectral broadband measurements and cloud products with high spatial resolution not seen before. MODIS cloud products (information available online at <http://daac.gsfc.nasa.gov/MODIS/products.shtml>) include, but are not limited to, the cloud mask (Ackerman et al. 1998) that provides each MODIS 1-km pixel with a clear index (confident clear, probably clear, confident cloudy, probably cloudy), the cloud-phase mask (Strabala et al. 1994; Baum et al. 2000) with 1-km resolution that provides each MODIS 1-km pixel with a phase index (water clouds, ice clouds, mixed phase, etc.), the cloud classification mask (CCM) with 1-km resolution (Li et al. 2003), the CTP and ECA from MODIS carbon dioxide (CO_2) band measurements with 5-km spatial resolution (Frey et al. 1999), and the CPS and COT with 1-km spatial resolution (King et al. 2003; Platnick et al. 2003).

MODIS measurements provide the crucial information to quantify ice water content for optically thin cirrus (King et al. 1992), enabling a global assessment of IWP in cirrus clouds. IWP measurements are urgently needed for the evaluation of cloud forcing, net radiation balance, and cloud formation and parameterization in general circulation models.

The AIRS (see information online at <http://www-airs.jpl.nasa.gov>; Aumann et al. 2003) on NASA's EOS *Aqua* satellite is a high-spectral-resolution ($\nu/\Delta\nu = 1200$, where ν is the wavenumber and $\Delta\nu$ is the width of a band) IR sounder with 2378 channels. AIRS measures radiances in the IR region 3.74–15.4 μm , which, together with the Advanced Microwave Sounding Unit (AMSU), yields the vertical profiles of atmospheric temperature and water profiles from the earth's surface to an altitude of 40 km with horizontal resolution of approximately 45 km (the AMSU footprint covers 3 by 3 AIRS footprints) (Susskind et al. 2003). Taking advantage of high-spectral-resolution AIRS longwave cloud-sensitive radiance measurements, CTP and ECA in theory can be retrieved with better accuracy than that from MODIS (Li et al. 2004b). AIRS is also suited for cloud microphysical property sensing such as CPS (in diameter) and COT with its high-spectral-resolution

IR radiances during both the daytime and nighttime, although hyperspectral IR radiance is most sensitive to CPS and COT in only finite ranges of values (Huang et al. 2004b). LWP or IWP can then be inferred from CPS, COT, and the mean extinction efficiency of the clouds.

The focus of this paper is to demonstrate the cloud property information and to derive high-quality cloud microphysical properties such as CPS and COT from the synergistic use of MODIS and AIRS during both the daytime and nighttime. Our approach takes advantage of the significant amount of spectral and spatially independent information provided by the MODIS and AIRS sensors. For example, the operational MODIS cloud mask and cloud-phase mask (CPM) with 1-km spatial resolution collocated to the AIRS footprints provide better AIRS subpixel cloud detection and phase determination because of the MODIS VIS/NIR and 8.5- μm spectral bands (AIRS has coarser spatial resolution and does not have 8.5- μm channels). Those derived cloud products from MODIS/AIRS will be available for the studies of some significant weather events such as tropical cyclone genesis, intensification, and rainfall of the TCSP.

Studies have shown that CTP and ECA can be derived from AIRS CO_2 absorption region (650–790 cm^{-1} or 15.38–12.66 μm) radiances or combination of AIRS CO_2 radiances and MODIS cloud products from CO_2 spectral bands. The CTP and ECA retrievals from combination of AIRS radiance measurements and the MODIS cloud products from CO_2 bands are better than those from MODIS alone; they are also slightly better than those from AIRS alone (Li et al. 2004b) when compared with ground observations. The EOS MODIS/AIRS provide quantitative information on COT and cloud water and ice content that should help to overcome shortcomings in the treatment of cloud processes in climate models and the lack of the observational constraints needed to characterize these processes accurately or to validate models. The MODIS/AIRS cloud products will improve and validate cloud information derived from other EOS satellites, as well as the operational weather and environmental satellites.

Algorithms have been developed for retrieving cloud microphysical properties from visible, near-IR, and IR multispectral bands (Nakajima and King 1990; Ou et al. 1999; Minnis et al. 1993a,b; Heidinger 2003; Cooper et al. 2003). They usually work well during the daytime because of cloud-sensitive solar illumination measurements. High-spectral-resolution IR sounder data such as AIRS are able to provide consistent cloud microphysical properties during both the daytime and night-

time. Use of advanced sounder data such as aircraft-based High-Resolution Interferometer Sounder (HIS) (Smith et al. 1993; Kahn et al. 2003) and EOS AIRS for analyzing the ice cloud optical thickness property has been also investigated (Huang et al. 2004a; Wei et al. 2004). However, quantitative retrieval of COT and CPS from AIRS has not been routinely made. In this paper, a fast cloudy radiative transfer model is developed to retrieve the COT and CPS simultaneously with one-dimensional variational (1DVAR) and minimum residual (MR) approaches. Operational COT and CPS product from the high-spatial-resolution MODIS serves as background in the AIRS 1DVAR cloud retrieval (hereinafter referred to as MODIS + AIRS 1DVAR), and the cloud microphysical property retrievals can also be derived from AIRS radiances with the MR algorithm (hereinafter referred to as AIRS MR), which does not use MODIS COT and CPS as background. The algorithms derive cloud microphysical properties from synergistic use of MODIS and AIRS data during both the daytime and nighttime. The MODIS cloud mask (part of data product MYD35), cloud-phase mask (MYD06), and cloud microphysical property products (MYD06) along with the AIRS radiances are used for cloud microphysical property retrieval during the daytime, whereas MODIS cloud mask (MYD35) and cloud-phase mask (MYD06) along with AIRS radiances are used during both the daytime and nighttime. A simulation study shows that the accuracy of cloud microphysical property retrieval is sensitive to the error of CTP. The CPS and COT retrievals from AIRS MR have been compared with the operational MODIS cloud microphysical property products (MYD06). A high correlation between operational MODIS and AIRS MR was found for CPS and COT. MODIS provides cloud microphysical properties during the daytime with high spatial resolution, while AIRS provides cloud products from high-spectral-resolution radiances but at a relatively coarser spatial resolution during both the daytime and nighttime.

Synergistic use of a high-spatial-resolution imager, along with information from a high-spectral-resolution IR sounder, described in this paper, is analogous to instruments planned for the next-generation Geostationary Operational Environmental Satellite (GOES)-R instruments (Gurka and Schmit 2004)—the Advanced Baseline Imager (ABI) (Schmit et al. 2005) and the Hyperspectral Environmental Suite (HES)—as well as the Visible Infrared Imaging Radiometer Suite (VIIRS) and Cross-Track Infrared Sounder (CrIS) on the National Polar-Orbiting Operational Environmental Satellite System (NPOESS). It can also be applied to pro-

cess EOS direct-broadcast MODIS/AIRS data (Huang et al. 2004a).

Section 2 describes the fast cloud radiative transfer model for calculating the AIRS longwave cloudy radiances. Section 3 analyzes the cloud information and sensitivity from AIRS longwave radiances. Section 4 describes the 1DVAR and MR schemes for the cloud microphysical property retrieval. Section 5 presents some simulation results and retrieval error analysis. Section 6 compares the operational MODIS cloud products with the MODIS + AIRS 1DVAR and the AIRS MR cloud microphysical property retrievals. The results and implications are discussed in section 7. Future extensions and conclusions are summarized in section 8.

2. Fast cloudy radiative transfer model

Through the joint efforts of the University of Wisconsin—Madison and Texas A&M University, a fast radiative transfer cloud model for hyperspectral IR sounder measurements has been developed (Wei et al. 2004). For ice clouds, the bulk single-scattering properties of ice crystals are derived by assuming aggregates for large particles ($>300 \mu\text{m}$), hexagonal geometries for moderate particles ($50\text{--}300 \mu\text{m}$), and droxtals for small particles ($0\text{--}50 \mu\text{m}$) (Yang et al. 2001, 2003). For water clouds, spherical water droplets are assumed, and the classical Lorenz–Mie theory is used to compute their single scattering properties. In the model input, the cloud optical thickness is specified in terms of its visible optical thickness at $0.55 \mu\text{m}$. The IR COT for each AIRS channel can be derived through the following relationship:

$$\tau = \frac{\langle Q_e \rangle}{2} \tau_{\text{vis}}, \quad (1)$$

where τ is the cloud optical thickness and $\langle Q_e \rangle$ is the bulk mean extinction efficiency. Given the visible COT and CPS, the IR COT, the single-scattering albedo, and the asymmetry factor can be obtained from a pre-described parameterization of the bulk radiative properties of ice clouds and water clouds. The detailed parameterization scheme has been reported in previous work (Wei et al. 2004). The cloudy radiance for a given AIRS channel can be computed by coupling the clear-sky optical thickness and the cloud optical effects. The cloud optical effects are accounted for by using a pre-computed lookup table of cloud reflectance and transmittance on the basis of fundamental radiative transfer principles. The clear-sky optical thickness is derived from a fast radiative transfer model called Stand-Alone

AIRS Radiative Transfer Algorithm (SARTA) (Hannon et al. 1996; Strow et al. 2003; see information online at <http://asl.umbc.edu/pub/rta/sarta/>); it has 100 pressure layers (101 pressure levels), with vertical coordinates from 0.005 to 1100 hPa. The computation takes into account the satellite zenith angle, absorption by well-mixed gases (including nitrogen, oxygen, etc.), water vapor (including the water vapor continuum), ozone, and carbon dioxide. Studies show that the slope of an IR cloudy brightness temperature (BT) spectrum between 790 (12.6 μm) and 960 (10.4 μm) cm^{-1} is sensitive to the CPS and the cloudy radiances are sensitive to COT in the region from 1050 (9.5 μm) to 1250 (8 μm) cm^{-1} for ice clouds (Huang et al. 2004b; Wei et al. 2004). The root-mean-square (rms) difference between the IR fast cloud model and the discrete ordinates radiative transfer (DISORT; Stamnes et al. 1988) calculation is less than 0.5 K for most AIRS spectral channels (Wei et al. 2004). Figure 1 shows the AIRS BT calculations at nadir view for ice clouds with various COTs and CPSs. A tropical atmosphere with a CTP of 300 hPa is used in the calculation. In the cloudy radiative transfer model, the clouds are treated as being optically thick but physically thin. Therefore, the cloud-base height is not assumed in the model (Wei et al. 2004). There are very good radiance signals for COT and CPS in the AIRS longwave window region, indicative of cloud microphysical properties retrievable from the AIRS longwave window regions (790–950 and 1050–1130 cm^{-1}) radiance measurements.

3. Sensitivity of AIRS longwave window radiances to cloud microphysical properties

With the fast cloudy radiative transfer calculation, the sensitivity of the AIRS longwave window (790–1130 cm^{-1} or 8.85–12.66 μm) radiances to cloud microphysical properties can be analyzed. The magnitude for CPS sensitivity is the BT sensitivity (delta BT) resulting from changing CPS by 20%; the magnitude for COT sensitivity is the BT sensitivity (delta BT) resulting from changing COT by 20%. Figure 2 shows the CPS sensitivities for ice clouds (upper panel) and water clouds (lower panel) of AIRS wavenumbers ranging from 790 to 1130 cm^{-1} for a tropical atmosphere at nadir view. The surface skin temperature is set equal to the surface air temperature in the sensitivity calculations. The y ordinate is the COT from 0.01 to 100, and the x abscissa is the wavenumber for AIRS longwave channels with step size of $\Delta\nu$ for wavenumber ν , where $\nu/\Delta\nu = 1200$. The blue color indicates strong sensitivity; the red color shows an opposite but weak sensitivity. In general, ice clouds have larger CPS sensitivity than wa-

ter clouds; AIRS channels with wavenumbers between 900 and 1130 cm^{-1} (or 8.85–11.1 μm) have good CPS sensitivity when the COT is less than 5. CPS of very thick clouds (COT >10) or very thin clouds (COT <0.1) is more difficult to retrieve, according to Fig. 2. Other information analysis techniques (Rodgers 2000) can also be used to study the cloud microphysical sensitivity in IR radiances.

Note that both AIRS and MODIS only have IR radiances during nighttime; AIRS provides more spectral cloud property information than MODIS, whereas MODIS provides better spatial information. The AIRS cloudy radiative transfer model accounts for the effect of COT and CPS at all wavenumbers; only the wavenumber regions most sensitive to CPS and COT are selected in retrieval according to the sensitivity analysis (see Figs. 1 and 2). Using selected regions instead of all regions will retain cloud microphysical property information while making the computation efficient.

4. The MR and 1DVAR retrieval schemes

Given the AIRS-observed cloudy radiance R^m for each channel, then $R = R(T, q, T_s, \varepsilon_s, D_e, \tau_{\text{vis}})$, which has the form

$$\mathbf{Y} = F(\mathbf{X}) + \boldsymbol{\eta}, \quad (2)$$

where D_e is CPS in diameter, τ_{vis} is the COT at 0.55 μm , the vector $\boldsymbol{\eta}$ is the observation error vector including forward model uncertainty, and vector \mathbf{X} contains CPS and COT. The atmospheric temperature profile $T(p)$, moisture profile $q(p)$, and surface skin temperature T_s are assumed to be known from the European Centre for Medium-Range Weather Forecasts (ECMWF) forecast analysis, infrared surface emissivity ε_s is assumed to be 0.98 in the longwave region, \mathbf{Y} contains N satellite-observed cloudy radiances R^m , and $F(\mathbf{X})$ is the fast cloud radiative transfer model for calculating the IR cloudy radiances from the cloud state \mathbf{X} .

The AIRS MR method seeks the CPS and COT by minimizing the differences between the observations and the calculations using AIRS longwave channels (790–1130 cm^{-1} , or 8.85–12.7 μm). That is,

$$J_{\text{MR}}(\mathbf{X}) = [\mathbf{Y}^m - F(\mathbf{X})]^T \mathbf{E}^{-1} [\mathbf{Y}^m - F(\mathbf{X})], \quad (3)$$

where the vector \mathbf{X} contains the CPS and COT that need to be solved, \mathbf{Y}^m is the vector of the AIRS-measured cloudy radiances used in the retrieval process, and \mathbf{E} is the observation error covariance matrix, which includes instrument noise plus the assumed forward model error. To solve Eq. (3), three steps for CPS and COT retrieval are used in the MR scheme. In step 1,

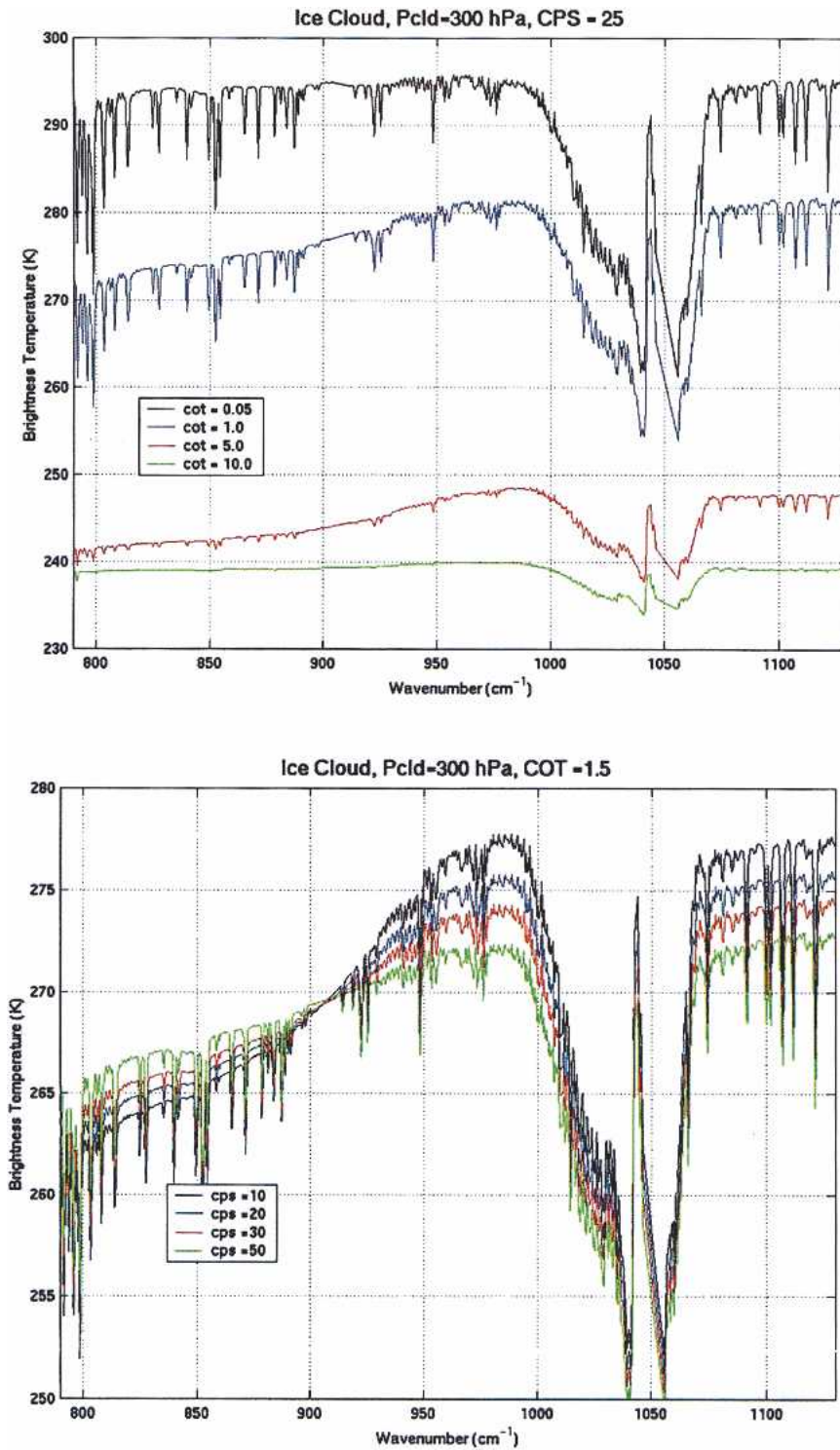


FIG. 1. AIRS (BT) calculations for ice clouds with various (top) COTs and (bottom) CPSs. A tropical atmosphere is used for the calculations.

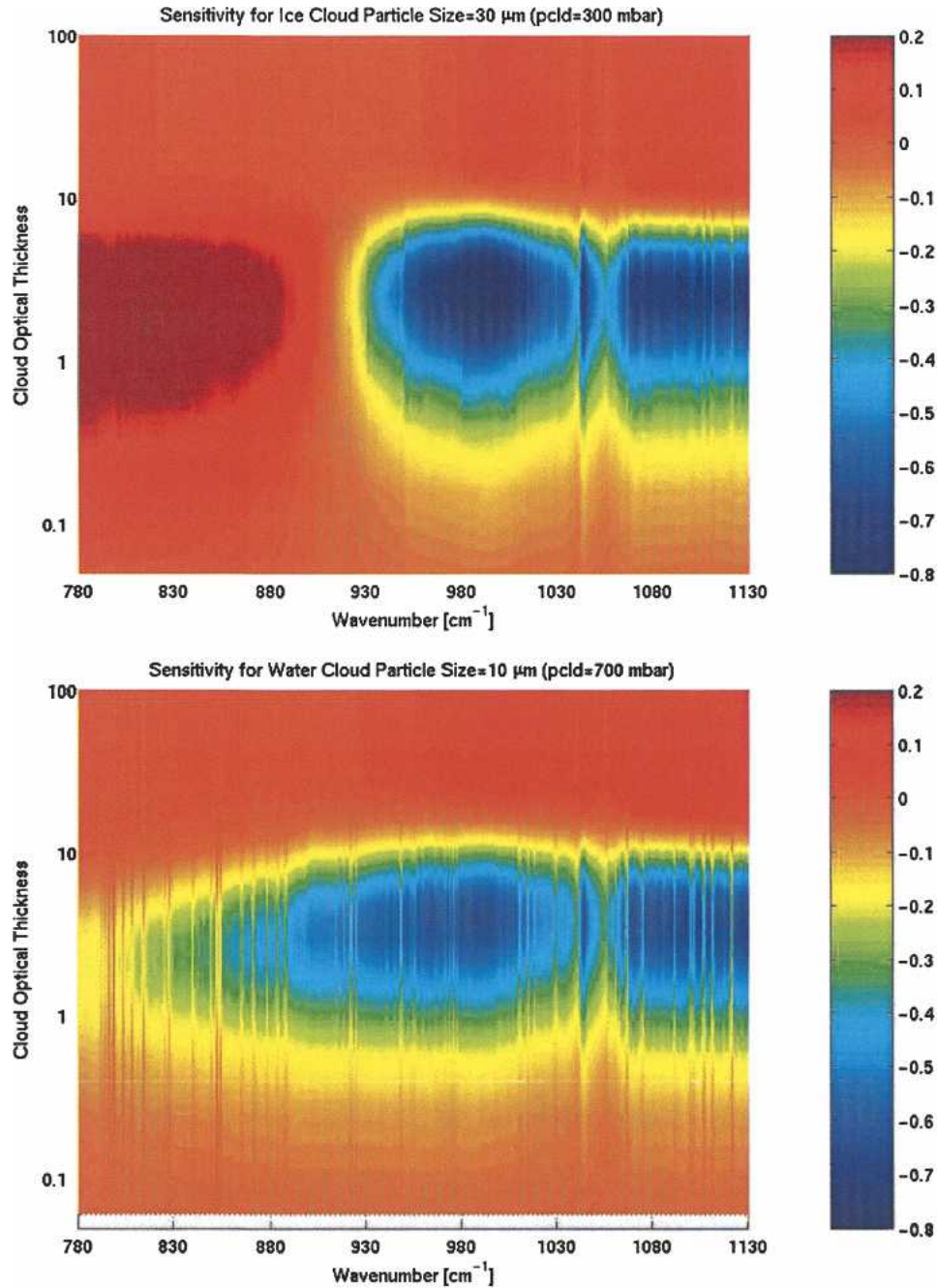


FIG. 2. Sensitivity of CPS for ice clouds and water clouds. A tropical atmosphere is used for the calculations. The unit of the color bar is BT difference (K).

with retrieved CTP and ECA from AIRS radiances of CO₂ channels (Li et al. 2004b), an initial COT is estimated as

$$\tau_{\text{vis}}^* = -2 \ln(1.0 - N_{\varepsilon_c}), \quad (4)$$

where N_{ε_c} is the ECA from AIRS radiances in the CO₂ region (700–790 cm⁻¹) (Li et al. 2004b) and τ_{vis}^* is the

initial COT. In step 2, with the initial COT, the CPS is retrieved with the MR scheme [Eq. (3)] using AIRS channels with wavenumbers between 790 and 960 cm⁻¹. In step 3, with retrieved CPS from step 2, the estimated COT is retrieved with the MR scheme [Eq. (3)] using AIRS channels with wavenumbers between 1080 and 1130 cm⁻¹. In practice, these three steps are iterated for

the improved retrieval of CPS and COT with the MR scheme.

To handle the nonlinearity of the cloud microphysical properties to the AIRS radiances, the MODIS + AIRS 1DVAR algorithm for CPS and COT retrievals uses the operational MODIS CPS and COT (King et al. 2003; Platnick et al. 2003) as the background information to obtain the cloud parameters from the AIRS longwave spectral-band cloudy radiance measurements. AIRS channels with wavenumbers between 790 and 1130 cm^{-1} are used in the CPS and COT retrieval. The linear form of Eq. (2) is

$$\delta \mathbf{Y} = \mathbf{F}' \cdot \delta \mathbf{X}, \quad (5)$$

where \mathbf{F}' is the linear or tangent model of the forward model \mathbf{F} , which is outlined by Eq. (2).

The 1DVAR approach is to minimize a penalty function $J(\mathbf{X})$; the general form of the 1DVAR solution (Eyre 1989) is given by

$$J(\mathbf{X}) = [\mathbf{Y}^m - \mathbf{F}(\mathbf{X})]^T \mathbf{E}^{-1} [\mathbf{Y}^m - \mathbf{F}(\mathbf{X})] + (\mathbf{X} - \mathbf{X}_B)^T \mathbf{B}^{-1} (\mathbf{X} - \mathbf{X}_B), \quad (6)$$

where \mathbf{X}_B is the background information inferred from the MODIS operational CPS and COT products and \mathbf{B} is the assumed background error covariance matrix that constrains the solution. To solve Eq. (6), a Newtonian iteration is used:

$$\mathbf{X}_{n+1} = \mathbf{X}_n + \mathbf{J}''(\mathbf{X}_n)^{-1} \cdot \mathbf{J}'(\mathbf{X}_n), \quad (7)$$

and the following quasi-nonlinear iterative form (Eyre 1989) is obtained:

$$\delta \mathbf{X}_{n+1} = (\mathbf{F}_n'^T \mathbf{E}^{-1} \cdot \mathbf{F}_n' + \mathbf{B}^{-1})^{-1} \cdot \mathbf{F}_n'^T \mathbf{E}^{-1} \cdot (\delta \mathbf{Y}_n + \mathbf{F}_n' \cdot \delta \mathbf{X}_n), \quad (8)$$

where $\delta \mathbf{X}_n = \mathbf{X}_n - \mathbf{X}_B$, $\delta \mathbf{Y}_n = \mathbf{Y}^m - \mathbf{Y}(\mathbf{X}_n)$, and \mathbf{F}_n' from Eq. (5) represents the linear terms with δR expansion of Eq. (2).

The background error covariance matrix \mathbf{B} is assumed to be diagonal with a standard deviation of 20% for the MODIS CPS and COT. The logarithms of CPS and COT are used to stabilize the solution of Eq. (8), and the background error is 0.2 for both $\ln D_e$ and $\ln \tau_{\text{vis}}$. The measurement error covariance matrix \mathbf{E} is a fixed diagonal matrix in which each diagonal element is η^2 [see Eq. (2)], that is, the square of the AIRS instrument noise plus the square of an assumed forward model error of 0.5 K for each longwave channel. The first-guess \mathbf{X}_0 , or the starting point of the iteration in Eq. (8), is also the MODIS CPS and COT product.

Quantifying the radiative transfer model uncertainty is very important for cloud microphysical property re-

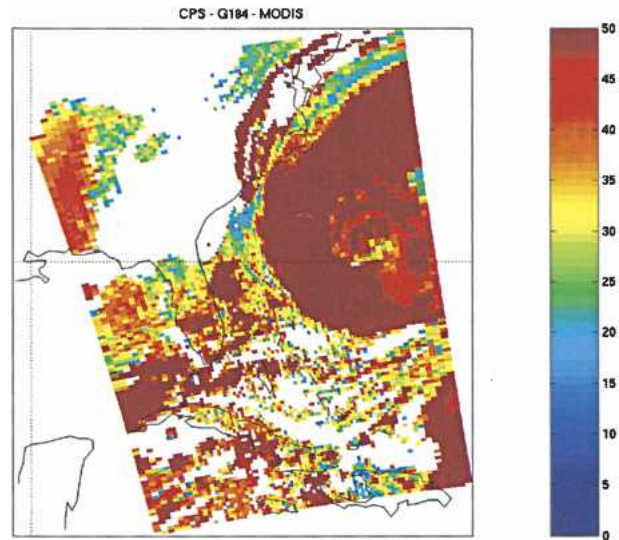


FIG. 3. MODIS CPS (μm) arithmetically averaged to the AIRS footprints for Hurricane Isabel.

trieval (Cooper et al. 2003). However, estimation of the model uncertainty, especially the bias, is difficult; based on the comparisons between the fast radiative transfer model and the DISORT model, the rms difference is less than 0.5 K in the AIRS longwave IR region for most cloud cases, and an uncertainty of 0.5 K is assumed as the model error. Note that 0.5 K might be conservative for the fast cloud radiative model; uncertainties resulting from variable ice crystal habits and size distribution, multilayered clouds, and so on, need to be quantified and included in future work.

Operational MODIS cloud microphysical property products with 1-km spatial resolution during the daytime (King et al. 2003; Platnick et al. 2003) provide the background information for the MODIS + AIRS 1DVAR retrieval. Figure 3 shows the MODIS CPS (in diameter) arithmetically averaged to the AIRS footprints for Hurricane Isabel at 1825 UTC 17 September 2003.

Both MODIS and AIRS data are synergistically used in the MODIS + AIRS 1DVAR and the AIRS MR scheme; both use the MODIS cloud mask and CPM for AIRS cloud detection and phase determination. The MODIS cloud mask, CCM, and CPM products provide AIRS sounder subpixel cloud characterization during the daytime and nighttime (Li et al. 2004a) as follows: (a) the collocated MODIS 1-km cloud mask indicates whether an AIRS footprint is clear or cloudy, (b) the collocated MODIS 1-km CPM indicates whether an AIRS subpixel contains water clouds, ice clouds, or mixed phase clouds—information that is required in the cloud microphysical property retrieval; (c) the collo-

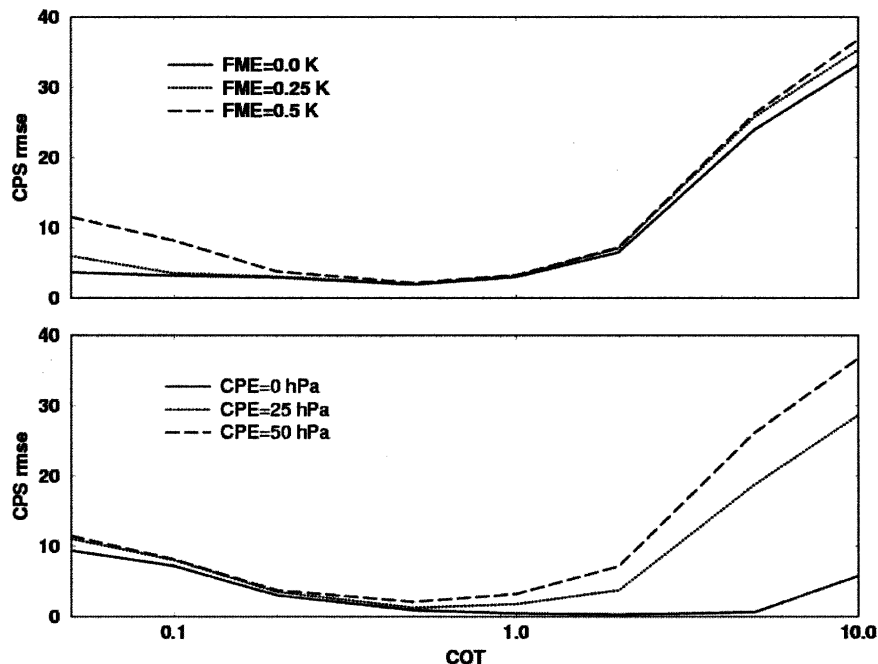


FIG. 4. Simulated CPS retrieval rmse as a function of COT.

cated MODIS 1-km CCM helps to determine whether an AIRS subpixel is partly cloudy or overcast and whether it is characterized by single-layer clouds or multilayer clouds. CCM can also be used to validate the ECA and COT retrievals.

5. A simulation study for the AIRS MR cloud microphysical property retrieval

To investigate the sources of errors in the cloud microphysical property retrieval with AIRS data, 450 radiosonde profiles from around the globe, representing various atmospheric conditions, were selected for this simulation. Fifty combinations were formed from each profile by assigning 50 COTs (0.04–100) and one CPS of $30 \mu\text{m}$ with $10\text{-}\mu\text{m}$ random variation corresponding to very thin to thick clouds; only ice clouds are assumed. The AIRS longwave cloudy radiances were simulated [using Eq. (2)] for all combinations for each profile. The AIRS instrument noise plus an assumed forward model error was randomly added into each AIRS channel cloudy radiance calculation. The simulation study focused on the following two configurations:

- 1) Assume that the CTP has an error of 50 hPa; an observation error—instrumental + forward model + other uncertainties—of 0.0, 0.25, and 0.5 K is assumed, respectively. This simulation will help to answer the question of how much improvement of

cloud property retrieval will there be if the radiative transfer model is perfect (no error) or improved (uncertainty reduced by one-half).

- 2) Assume that the observation has an error of 0.5 K; a cloud pressure error (CPE) of 0, 25, and 50 hPa is assumed, respectively.

For atmospheric temperature, a 1.5-K random error was assumed at each pressure level, which is close to the accuracy of the forecast model analysis, and a 15% error was included for water vapor mixing ratio at each pressure level. For the surface skin temperature a random error of 2.5 K was assumed, and a 0.015 error was included for the IR surface emissivity. Studies (Menzel et al. 1992; Wei et al. 2004) show that errors of the temperature profile from forecasts have less impact on cloud property retrieval than do other error sources such as the forward model uncertainty. Figure 4 shows the retrieved CPS root-mean-square error (rmse) with respect to truth as a function of COT; the upper panel reveals the results of configuration 1, and the lower panel reflects the results of configuration 2. It can be seen that the impact of observation error on retrieval is much less than that of CPE. With an error of 50 hPa for CTP, there is less difference between the retrievals with observation errors of 0.25 and 0.5 K; however, the CPS retrieval is significantly improved with the CPE reduced from 50 to 25 hPa, indicating that the CPE is the major error source for the CPS retrieval. Figure 4 also

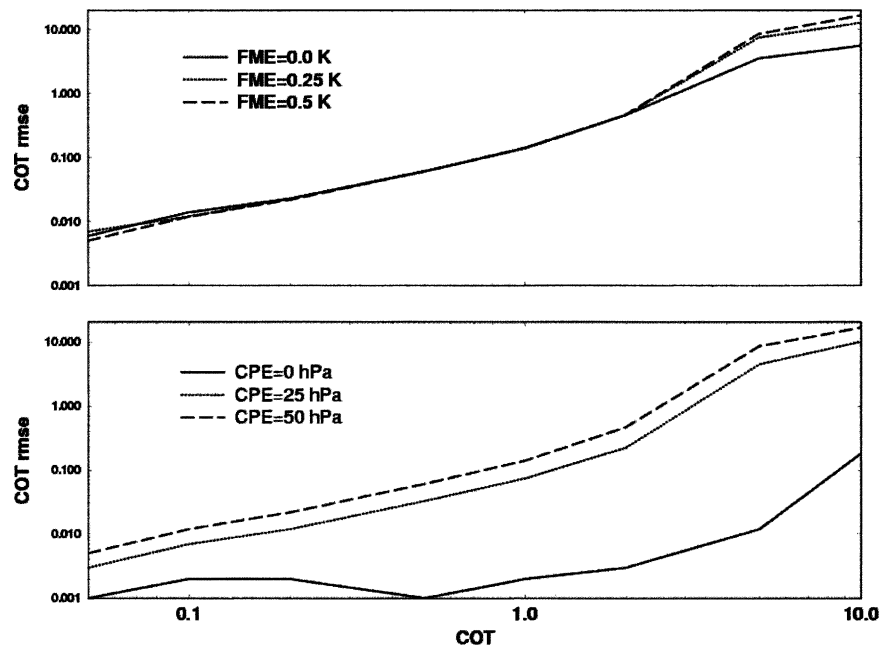


FIG. 5. Simulated COT retrieval rmse as a function of COT.

shows that when the clouds are very thin ($\text{COT} < 0.1$) or very thick ($\text{COT} > 5$), the CPS retrieval error is increased, which is consistent with the sensitivity analysis (see Fig. 2). Figure 5 is the same as Fig. 4, but for the COT-retrieval rmse. Again, CPE is the major source of error for the COT retrieval; thin clouds are easier to retrieve with regard to the COT and CPS than are thick clouds with the AIRS data. Based on the previous studies, the CPE from hyperspectral sounder data, such as AIRS data, is approximately 15–30 hPa for most clouds (Li et al. 2004b), and the CPE from MODIS is approximately 50 hPa (Frey et al. 1999).

6. Retrieval of cloud microphysical properties from MODIS and AIRS

A granule of AIRS data was studied. Each granule contains 135 lines, with each line containing 90 pixels. Figure 6 shows the AIRS (granule 184) longwave window channel 763 (901.69 cm^{-1}) BT images at 1825 UTC 17 September 2003 for Hurricane Isabel. The red color indicates a warm scene or clear skies, and the blue color represents a cold scene or cloudy skies. Boxes A1 and A2 in Fig. 6 indicate the two small areas on the hurricane center and edge. The 1-km MODIS pixels are collocated within an AIRS footprint with collocation accuracy better than 1 km provided that the geometry information from both instruments is accurate (Li et al. 2004a). Radiances from 14 MODIS spectral bands are used to estimate whether a given view of the earth's

surface is affected by clouds, aerosol, or shadow (Ackerman et al. 1998), and the MODIS operational cloud mask product MYD35 was used in this study. The AIRS footprint is determined to be cloudy for cloud retrieval only when the percentage of the clear MODIS pixels within the AIRS footprint is less than 97%. The atmospheric temperature and moisture profiles, as well as the surface skin temperature, are taken from the ECMWF forecast model analysis in both the 1DVAR and the MR retrievals.

Figure 7 shows the COT (upper panel), and the CPS (lower panel; μm) images with the MR algorithm. The CPS from the AIRS MR is similar to that from the operational MODIS (see Fig. 3) in pattern. However, the CPS retrievals inside the hurricane are a little noisy because AIRS radiance measurements are saturated for cloud microphysical properties when viewing opaque convective clouds and CPS information is limited. Figure 8 shows a scatterplot between the MR COTs and the MODIS + AIRS 1DVAR COTs (upper panel) for ice clouds of the same hurricane case; both the MODIS + AIRS 1DVAR and the AIRS MR obtain similar COT results, although MR does not use the MODIS COT and CPS background in retrieval, indicating that both methods are stable. However, the MODIS + AIRS 1DVAR is more computationally efficient than the AIRS MR. The scatterplot between the operational MODIS VIS/NIR COTs and the AIRS MR COTs for ice clouds is also shown in Fig. 8 (lower panel); the MODIS 1-km COTs are arithmetically av-

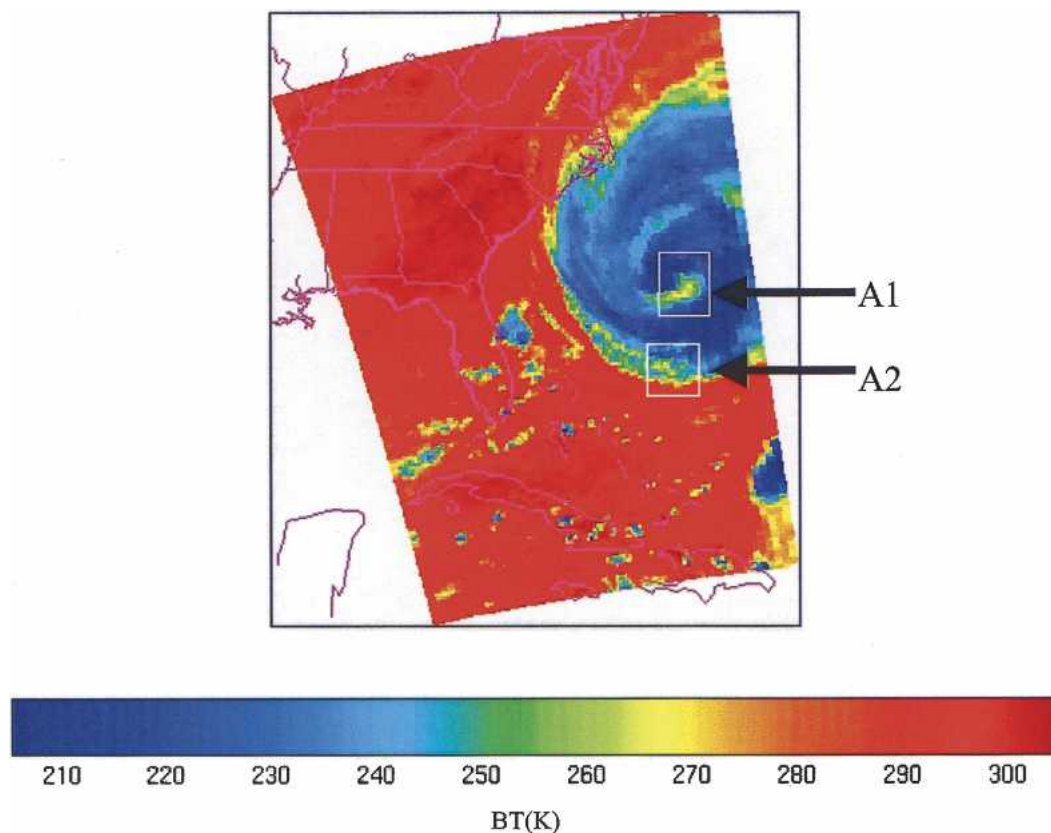


FIG. 6. AIRS BT image of granule 184 on 17 Sep 2003 for channel 763 (901.69 cm^{-1}); boxes A1 and A2 indicate two small areas near hurricane center and edge.

eraged to AIRS footprint, and the differences between MODIS VIS/NIR-derived COTs and AIRS IR-derived COTs are large. However, the correlation between the operational MODIS COTs and the AIRS IR COTs is high (greater than 0.75 in this case), revealing that AIRS is able to provide useful COT information during both the daytime and nighttime.

Several AIRS footprints are selected for more detailed analysis. Figure 9 shows the MODIS 1-km CCM superimposed on the AIRS footprints for boxes A1 (left panel) and A2 (right panel), shown in Fig. 6; three adjacent AIRS footprints (F1, F2, and F3) in box A1 representing three layers of thick clouds at the center of the hurricane indicated by the 1-km CCM are selected for a retrieval test. The upper panels of Fig. 10 show the AIRS spectra of BT observations (black line), BT calculations with the MODIS + AIRS 1DVAR (red line), and BT calculations with the AIRS MR (blue line) for the three footprints (F1: left panel; F2: middle panel; F3: right panel). The BT differences between the observations and the calculations for the three AIRS footprints are shown in the lower panels. The CTP retrievals (Li et al. 2004b) are different from the three foot-

prints, and they are well retrieved by the 1DVAR (185.779, 238.233, and 345.947 hPa) and the MR (200.989, 262.140, and 353.013 hPa). Also, the COT retrievals from the three adjacent footprints are consistent with ECA retrievals in both the MODIS + AIRS 1DVAR and the AIRS MR. Clouds are thicker outside the center than those inside the center. Calculations with both the MODIS + AIRS 1DVAR and the AIRS MR retrievals fit the observations well for all three footprints. Figure 11 is the same as Fig. 10, but for the three AIRS footprints in box A2 (see Fig. 6 for box A2) representing ice clouds (F5: left panel), ice clouds over water clouds (F4: middle panel), and scattered ice clouds over water clouds (F6: right panel), according to the MODIS 1-km CCM. The calculations fit the slope of the observations very well, indicating good sensitivity of AIRS radiance measurements to the microphysical properties for ice clouds.

Footprints F7 and F8 (see box A2 in Fig. 9) represent thin water clouds and thick water clouds, respectively, according to the MODIS CCM. The upper panel of Fig. 12 shows the AIRS BT observations, BT calculations with the MODIS + AIRS 1DVAR cloud proper-

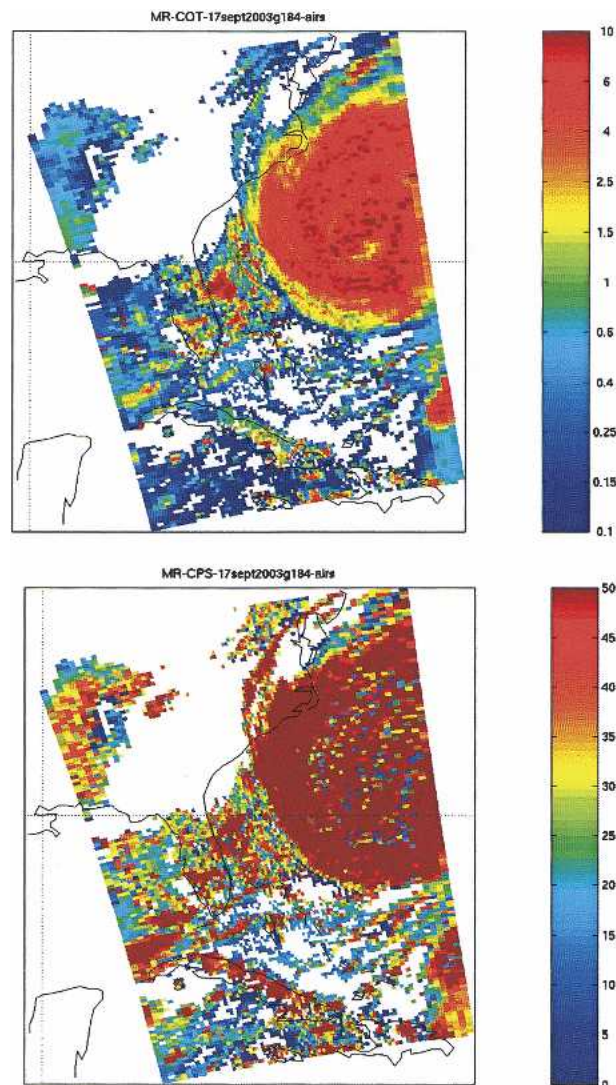


FIG. 7. (top) COT and (bottom) CPS (μm) images with MR algorithm.

ties, and BT calculations with the AIRS MR cloud properties for footprints F7 (left panel) and F8 (right panel). The BT differences between the observations and calculations for the two footprints are shown in lower panels. For F7, there are significant cloud property differences between the MODIS + AIRS 1DVAR and the AIRS MR; the AIRS MR-retrieved COT and ECA are more consistent with the MODIS CCM (thin clouds) than those retrieved from the MODIS + AIRS 1DVAR. Because the difference between the clear calculation and the observation is small for the MODIS 11- μm band, an IR window technique was applied for MODIS CTP that assigns a low cloud CTP and high ECA. In the IR window technique, the cloudy field-of-view is assumed to be overcast, and the CTP is found

by minimizing the BT difference between the observation and calculation from an IR window spectral band, for example, the 11- μm spectral band (Menzel et al. 1992). The window technique may introduce an increased CPE when the clouds are thin and low, resulting in imperfect CTP and ECA retrievals with the MODIS + AIRS 1DVAR (Li et al. 2004b). In such a situation, the cloud microphysical property retrieval will also be affected. Similarly, in footprint F8, the AIRS MR-retrieved COT and ECA are much smaller than that from the MODIS + AIRS 1DVAR, although the CCM indicates overcast low clouds for this footprint. Note that overcast clouds are not necessarily optically thick. In general, the MODIS + AIRS 1DVAR approach is efficient; it performs very well, except for in some cases in which the clouds are thin and low.

Clouds are very optically thick inside the hurricane while they are less optically thick in the hurricane center (eye), according to the study. Larger particles are found near the center of the tropical cyclone. The techniques can be applied to process MODIS/AIRS for cloud-property retrieval during both the daytime and nighttime. Figure 13 shows the AIRS BT image at a window channel (upper panel) and the COT retrieval image with the MR method on 2 September 2003; the MODIS cloud mask and CPM are used to help the AIRS COT and CPS retrievals, as mentioned above. The COT pattern is consistent with the AIRS BTs; the hurricane, thick clouds, and thin clouds are depicted well by COT retrievals.

7. Discussion

Synergistic use of MODIS and AIRS data provides a novel way to estimate the cloud properties. Taking advantage of the MODIS mask products (cloud mask, CCM, CPM) with 1-km spatial resolution, using MODIS microphysical cloud products (COT, CPS) as the background information in the AIRS variational retrieval, and using the abundant spectral information of the AIRS measurements to identify the cloud microphysical properties (CPS, COT), the cloud property retrievals can be derived during both the daytime and nighttime. For example, MODIS can provide AIRS with a good cloud mask because of its high spatial resolution, and it can also provide a reliable cloud-phase mask because of its 8.5- μm band, which is sensitive to cloud phase (AIRS does not have this spectral region). The CPE is the major source of error in the CPS and COT retrieval, according to the simulation. Aside from CPE, forward-model uncertainty and instrumental noise also exhibit impact on the retrievals.

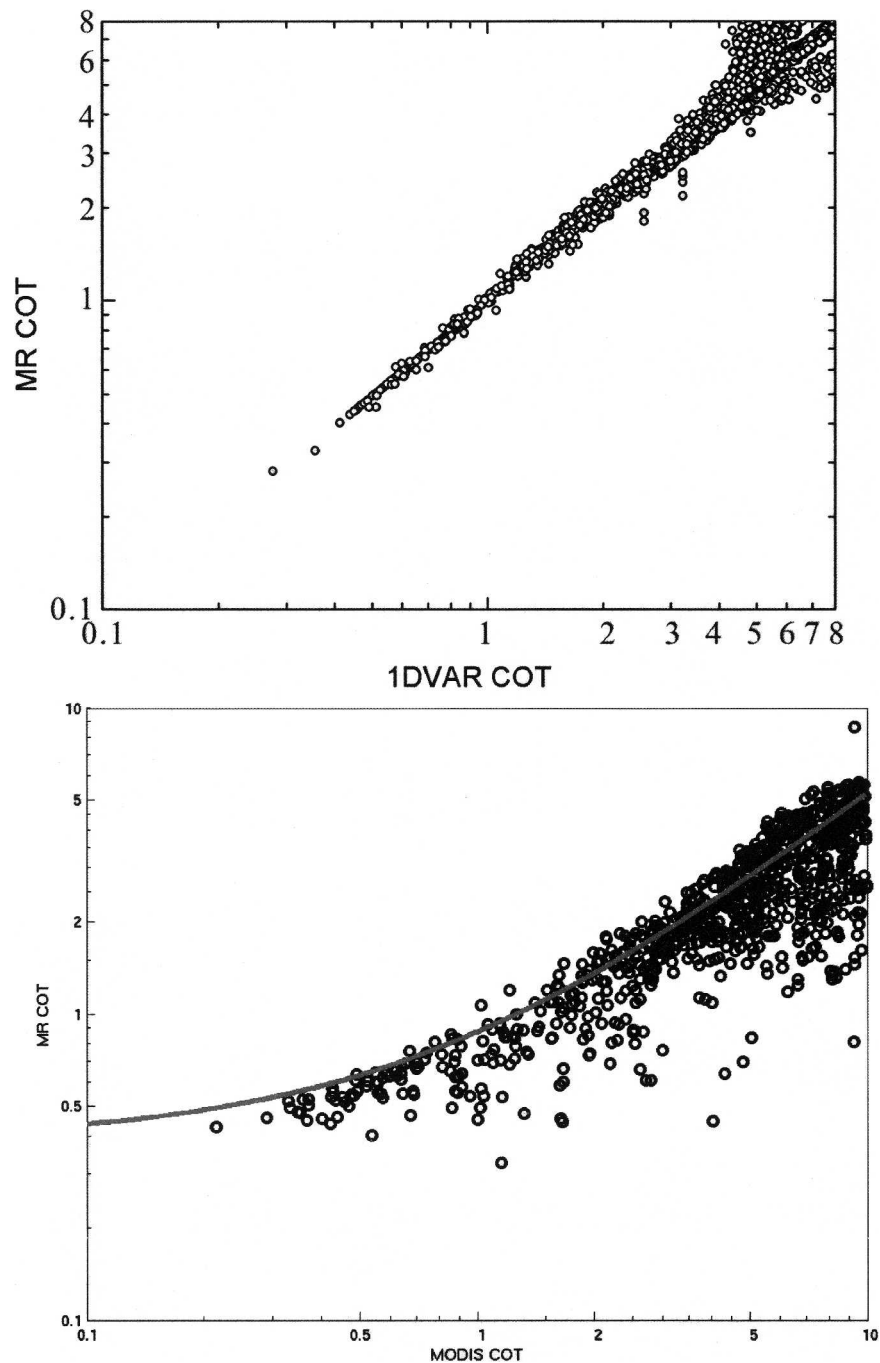


FIG. 8. (top) Scatterplot between the MODIS + AIRS 1DVAR COTs and the MR COTs for ice clouds of Hurricane Isabel, and (bottom) scatterplot between the MODIS VIS/NIR COTs and AIRS MR COTs for ice clouds.

A realistic fast radiative transfer model able to simulate the real cloud situation is crucial for cloud microphysical property retrieval. Diversified ice crystal shapes need to be included in the radiative transfer model. At this time only single-layer clouds are assumed in the cloud radiative transfer model; for ex-

ample, when there is ice over water clouds, only the ice cloud situation is considered in the retrieval, and the CPS and COT retrievals might be biased from the “true solution,” although the calculations fit the observations very well. A fast cloudy radiative transfer model addressing two-layer clouds, especially the ice-over-water

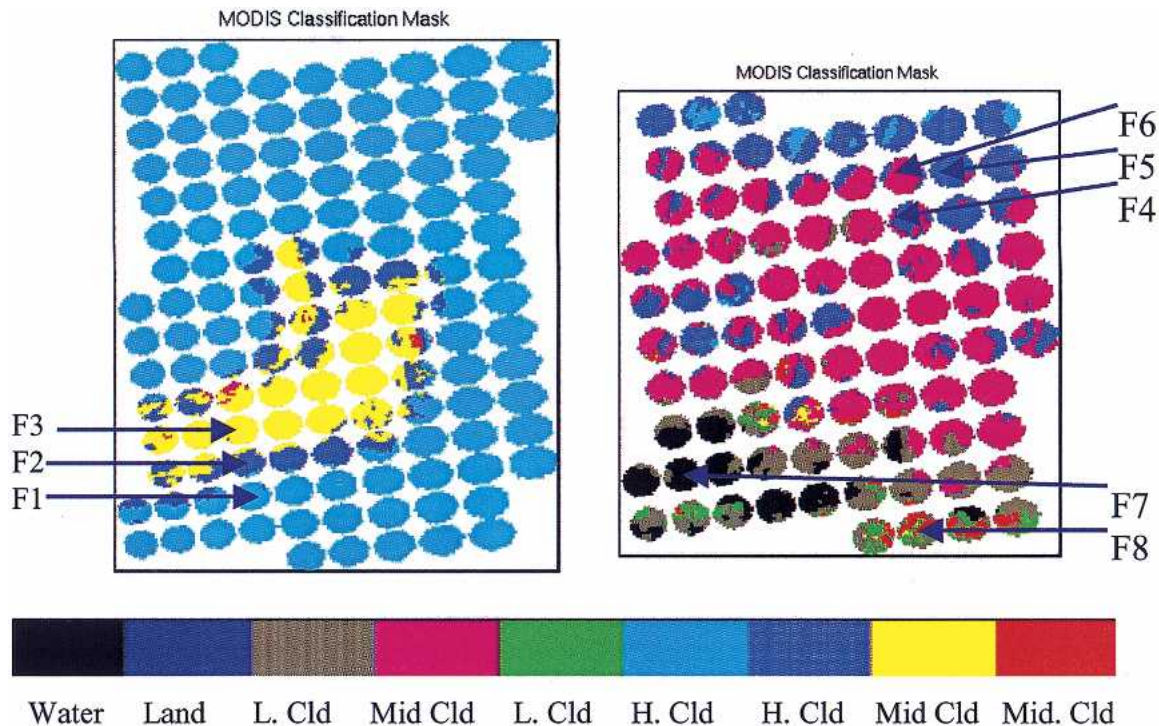


FIG. 9. MODIS 1-km CCM superimposed on AIRS footprints for boxes A1 and A2 shown in Fig. 6: L. Cld is low clouds, H. Cld is high clouds, and Mid. Cld is medium-level clouds.

situation, is under development. In general, IR sounders can determine the cloud-top height very well, and they can also retrieve the cloud microphysical properties with good accuracy for semitransparent cirrus clouds (Wei et al. 2004); however, the retrieval accuracy is degraded when clouds are thick because of lack of penetration into the cloud of the IR radiance measurements (see Figs. 2–5).

Validation of cloud microphysical properties is always difficult. However, there are some indicators on

the accuracy of CPS and COT. The first is that AIRS calculations using retrieved COT and CPS fit the observations within an acceptable level, as shown in Figs. 10–12. The BT residuals between the calculations and observations, along with the rms of the noise-equivalent temperature difference (NeDT) from all of the AIRS cloudy footprints (8094 successful retrievals) in the granule, are shown in Fig. 14. The BT residual rms with both the MODIS + AIRS 1DVAR and the AIRS MR are less than 1.5 K (although larger than

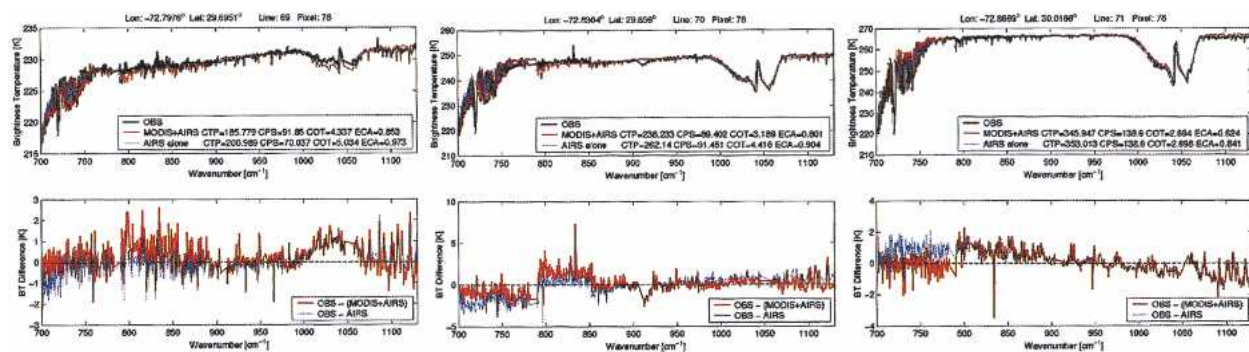


FIG. 10. (top) AIRS spectra of BT observations (black line), BT calculations with 1DVAR (MODIS + AIRS, red line), and BT calculations with MR (AIRS alone, blue line) for AIRS footprints of (left) high clouds (F1), (middle) middle-high clouds (F2), and (right) middle clouds (F3), respectively. (bottom) The BT differences between the observations and the calculations for the three AIRS footprints.

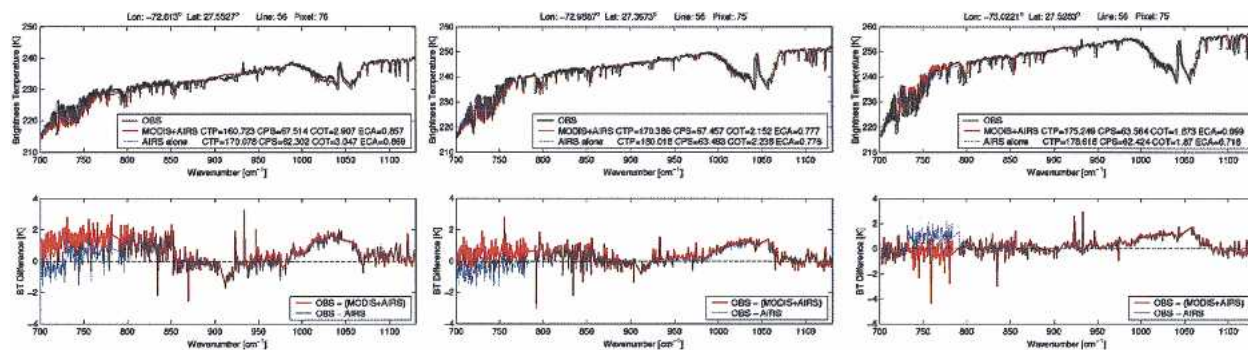


FIG. 11. (top) AIRS spectra of BT observations (black line), BT calculations with 1DVAR (red line), and BT calculations with MR (blue line) for AIRS footprints of (left) ice clouds (F5), (middle) ice clouds over water clouds (F4), and (right) scattered ice clouds over water clouds (F6). (bottom) The BT differences between the observations and the calculations for the three AIRS footprints: OBS - (MODIS + AIRS) means observations minus calculations from the MODIS + AIRS 1DVAR retrieval, and OBS - AIRS means observations minus calculations from the MR retrieval.

the AIRS rms NeDT) for most AIRS window channels; this indicates that the algorithm performs reliably. The MODIS + AIRS 1DVAR and the AIRS MR have similar residuals for the AIRS channels between 790 and 920 cm^{-1} , suggesting that the CPS retrievals should be close between the MODIS + AIRS 1DVAR and the AIRS MR. However, the AIRS MR has smaller residuals than the MODIS + AIRS 1DVAR for AIRS channels between 930 and 1130 cm^{-1} , indicating that MODIS VIS/NIR COT might be much larger than the actual AIRS IR COT solution, because of the optical difference between the VIS/NIR and the IR observations. The second is that cloud-property retrievals such as COT and ECA can also be verified using the MODIS 1-km classification mask (Li et al. 2004a,b). For example, the ECA and COT retrievals in Figs. 10 and 11 are consistent with the

MODIS 1-km classification mask, indicating the reliability of the cloud property retrievals with MODIS/AIRS data.

Although cloud microphysical property remote sensing using the IR method is not new, retrieval of cloud microphysical properties from a hyperspectral IR such as the AIRS sounder is relatively new; we believe that it is useful to investigate the cloud information and develop an efficient procedure to derive cloud properties from hyperspectral IR data during both the daytime and nighttime with help from multispectral-band imager data with high spatial resolution. This work will benefit our future operational processing of CrIS on NPOESS and HES on GOES-R, for example, using VIIRS to help CrIS and ABI to help HES for cloud microphysical property retrieval during both the daytime and nighttime.

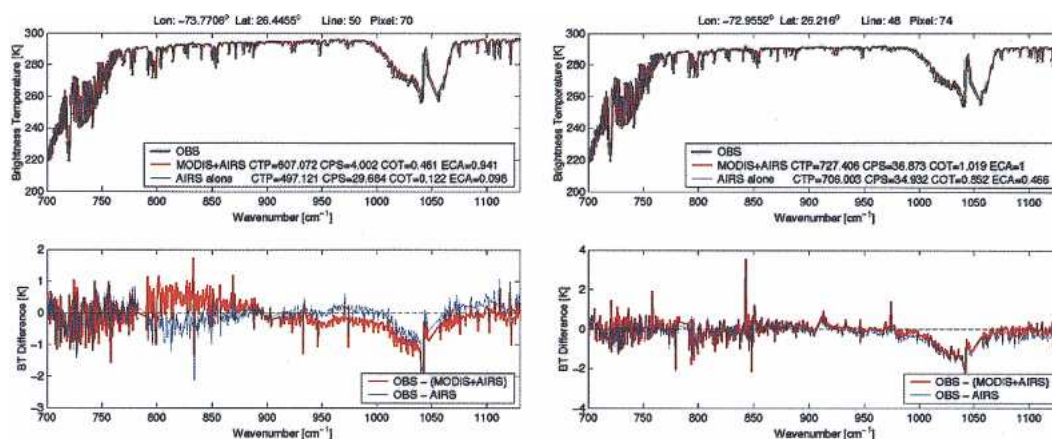


FIG. 12. (top) AIRS spectra of BT observations (black line), BT calculations with 1DVAR (red line), and BT calculations with MR (blue line) for the (left) thin water clouds (F7) and the (right) thick water clouds (F8). (bottom) The BT differences between the observations and the calculations for the two AIRS footprints.

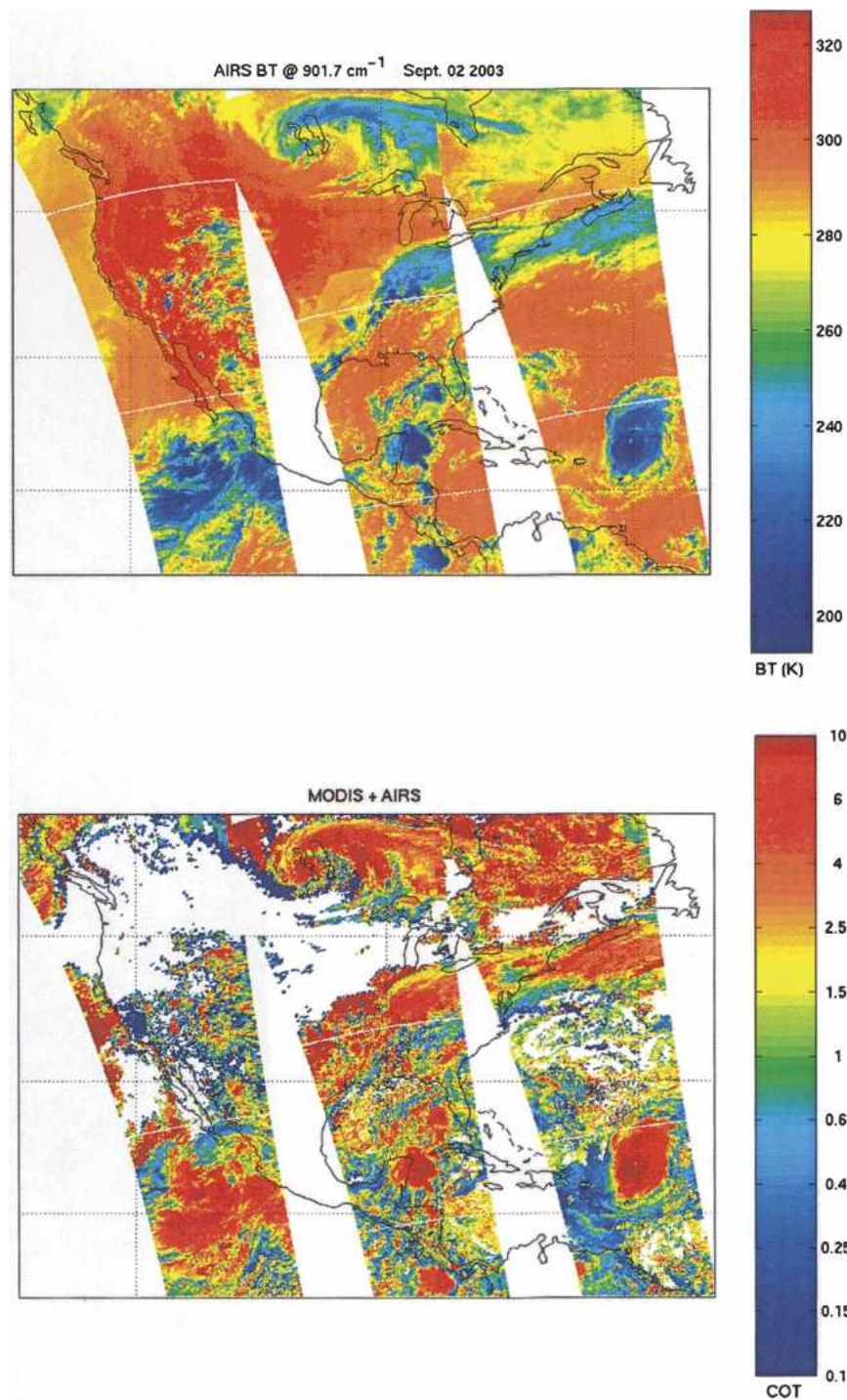


FIG. 13. (top) The AIRS BT image at a window (901.69 cm^{-1}) channel and (bottom) the COT retrieval image with MR method on 2 Sep 2003. MODIS cloud mask and CPM are used to help the AIRS COT retrieval.

8. Summary and conclusions

Two approaches for synergistic use of the MODIS mask products (cloud mask, CPM, and CCM), the op-

erational MODIS cloud microphysical cloud products, and the AIRS radiance measurements for retrieving the CPS and COT are described in this paper.

The MODIS cloud mask, CCM, and CPM with 1-km

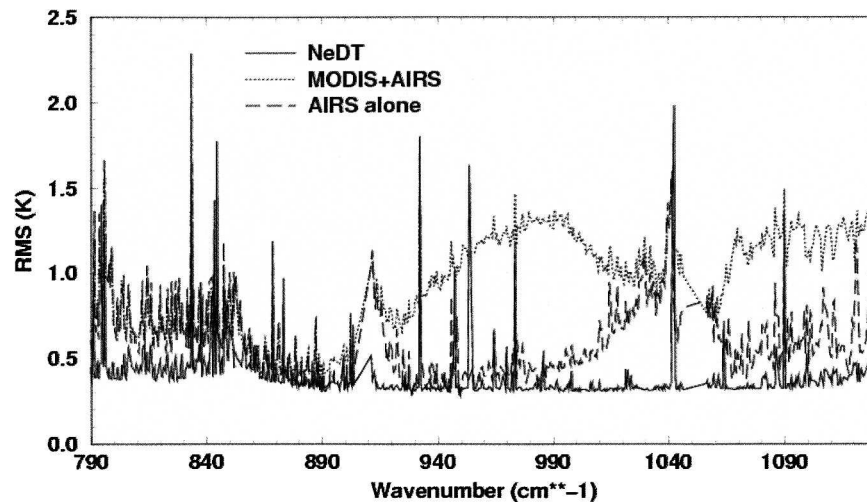


FIG. 14. The BT rms residuals from NeDT (solid line), the MODIS + AIRS 1DVAR retrievals (dotted line), and the AIRS-alone MR retrievals (dashed line).

spatial resolution are used to characterize the AIRS subpixel cloud condition (clear/cloudy, ice/water, single/multilayer) during both the daytime and nighttime. 1DVAR is used for cloud microphysical property retrieval with the operational MODIS COT and CPS as the background information during the daytime, while MR can be used for cloud microphysical property retrieval during both the daytime and nighttime.

Unlike the CTP and ECA retrieval (Li et al. 2004b), the cloud microphysical property retrieval from the MODIS + AIRS 1DVAR is not shown to be better than either the operational MODIS product or the AIRS MR retrieval; this is due to the fact that the operational MODIS product is derived from the VIS/NIR observations, whereas the MODIS + AIRS 1DVAR and AIRS MR algorithms seek the COT and CPS solutions by fitting the calculations with IR observations. Comparison between IR and VIS/NIR for cloud microphysics should be carefully investigated. For thin cirrus clouds that are invisible in visible bands IR has the advantage; for thick clouds VIS/NIR should be better. The MODIS + AIRS 1DVAR is similar to the AIRS MR for COT and CPS retrieval in most situations, but it is more computationally efficient. The COTs from the AIRS MR are different from those of the operational MODIS product, but there is good correlation between them.

In summary, (a) MODIS mask products (cloud mask, CPM, and CCM) help the cloud microphysical property retrievals in both the MODIS + AIRS 1DVAR and the AIRS MR by identifying the clear coverage and cloud phase within AIRS subpixels; (b) MODIS mask products can also be used to verify the cloud property retrieval (e.g., AIRS COT retrieval should be consistent

with MODIS cloud fraction and ECA within the AIRS subpixel) and to guide the two-layered cloud property retrieval (e.g., using MODIS CCM) in our future work; (c) the MODIS + AIRS 1DVAR provides efficient cloud property retrievals from AIRS radiance measurements during day, and the AIRS MR provides the cloud microphysical property retrievals from the AIRS radiance measurements during both the daytime and nighttime.

Multilayer clouds occur often for the AIRS footprints. The effective CTP is derived for the multilayer cloudy footprints (see Fig. 12). More accurate retrieval of multilayer cloudy microphysical properties requires an efficient fast multilayer cloudy radiative transfer model, which is currently under development. It also requires accurate CTP for every cloud layer.

The following specific conclusions can be made:

- 1) AIRS window channels ($790\text{--}1130\text{ cm}^{-1}$) provide abundant information of cloud microphysical properties.
- 2) Error of the CTP estimate is the major source of error in the cloud microphysical property retrieval with IR sounder data.
- 3) There are limitations on the cloud microphysical property retrieval from AIRS observations when the clouds are very thick ($\text{COT} > 10$) or very thin ($\text{COT} < 0.1$).
- 4) The MODIS mask products (cloud mask, CCM, and CPM) are very important in retrieving the cloud properties.
- 5) MODIS and AIRS data provide unprecedented information on cloud properties (CTP, ECA, COT, and CPS) to support tropical cyclone studies. The

AIRS MR products during both the daytime and the nighttime, as well as the MODIS + AIRS 1DVAR cloud properties during the daytime, can be derived for the study of significant weather events such as tropical cyclone genesis and intensification.

The independent validation of cloud property products with synergistic use of MODIS and AIRS is ongoing by comparison with other available measurements, such as lidar observations, pilot reports, radiosonde observations, and in situ cloud measurements, as well as cloud measurements from other EOS satellites and operational weather and environmental satellites. Measurements during TCSP will also be collected for validating the MODIS/AIRS cloud properties. A cloud model handling two-layered clouds (e.g., ice over water) is also under development; the variable crystal habits will also be considered in the model in future work.

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